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COMMENTS ON TEC TRENDS

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SUMMARY

Listing and discussing some thermionic-energy-conversion (TEC) trends results in a brief text - backed by many more pages of figures, tables, references, and appendixes. Projections of TEC performance, overall powerplant efficiency, and cost of electricity (COE) lead again to observations on the importance of "high-temperature, high-power-density TEC" (NASA TM X-73844) and the need to "optimize. . .TEC" for the system (NASA TM X-73892) rather than assuming that low-current densities are desirable. Partial optimization of steam-plant topping with >20 W/cm^2 TEC yields overall efficiencies near those of the most-efficacious advanced systems and COE's between the best and those for conventional steam plants. Of course, complete optimization of TEC-topped plants should produce even better efficiency and COE values. Major R&T requirements for such application payoffs are rapid TEC-performance improvements coupled with detailed determinations of low-cost effective materials, fabrication techniques, and maintenance procedures. TEC trends are in the right direction.

PAST TEC TRENDS

Thermionic energy conversion (TEC) is a young technology. But it has evolved rapidly (refs. 1 to 5). The impetus for this growth derived primarily from space nuclear power (SNP) activities prior to 1973. In contrast to that in-core TEC program, however, present research and technology (R&T) emphasizes out-of-core TEC with heat-pipe-cooled reactors (refs. 1 to 19). In addition TEC potentialities for terrestrial power generation attract increasing attention (refs. 20 to 30). Proposals for such applications comprise simple all-TEC systems (refs. 28 and 29), TEC topping of central-station powerplants (refs. 20 to 27 and 30), and even TEC bridging of the Carnot-efficiency gap between magnetohydrodynamic (MHD) topping and steam-driven generators (refs. 24 and 29). Although mentioning MHD and TEC with steam invariably evokes the "compounding advanced technologies" warning, existence of Department of Energy (DOE) programs for MHD and TEC practically compels prudent evaluation of their combined effects.

Ultimate TEC desirability in various applications depends strongly on the calendar of performance improvements. So predictions of this time table appear increasingly in recent TEC publications (refs. 1, 7, and 30). And

because of their importance the present paper comments on these published and projected TEC performance trends. This commentary includes graphs and an appendix relating TEC performance parameters, plots of predicted and actual TEC trends, a figure relating projected cost of electricity to overall efficiency for TEC topping, and a discussion of the implications of these relationships.

TEC PERFORMANCE

Perhaps the most important criterion for TEC performance is efficiency (Appendix: ref. 4). But output power density and voltage as well as interelectrode and total-internal losses also receive considerable emphasis in TEC R&T discussions. So for the reader's convenience these and other variables as well as their definitions appear in the appendix: "Some TEC Background and Theory" (excerpted from ref. 18). Because the appendix presentation aims at space applications, the present paper also includes results based on the same assumptions, but related more to TEC use in topping cycles for terrestrial applications (figs. 4 to 11).

This background and performance information may make the discussion of TEC trends more meaningful.

SOME TEC-PERFORMANCE PROJECTIONS

Representative indications of TEC trends appear in figures 12 (ref. 1), 13 (ref. 7), and 14 (ref. 30) as well as Table 3 (ref. 7). In these presentations "barrier index" and "performance index" correspond to "total internal losses" (indicated in the appendix) and produce identical effects on appropriate electron-potential diagrams for thermionic converters. Figures 4 to 7 as well as 13 and 14, Table 3, and the appendix all relate such internal-loss values to TEC efficiencies.

Figure 12 depicts the history of TEC performance with total internal losses of 2.8 eV at the beginning of 1968; 2.4, 1970; 2.0, 1972; and 1.9, 1975. The arbitrary definitions of "first-," "second-," and "third-generation" TEC (2.0-, 1.5-, and 1.0-eV total internal losses) also appear in figure 12.

Figure 13 and Table 3 look into the TEC-performance future fiscally and temporally. Interestingly, as reference 4 (Table 3) foretold in 1976, attainment of 1.7-eV total internal losses occurred prior to the end of fiscal year 1978: Scientists at the Sukhumi Institute of Physics and Technology reported this unpublished accomplishment to a NASA, ERDA TEC-Tour group in the USSR during July of 1977 (ref. 29). A recent publication of those results (ref. 31) shows that the lanthanum-hexaboride collector (background: refs. 32 and 33) used in the Sukhumi TEC experiments produced

a 1.2-eV cesiated work function. That value would allow a common 0.5-eV interelectrode drop and still yield 1.7-eV total internal losses.

With such a 1.2-eV collector the near-zero interelectrode losses prophesized to be available in FY 1981 by reference 6 of the appendix would mean 1.2-eV total internal losses in that year.

In contrast reference 30 (fig. 14) predicts 1.2-eV total internal losses in FY 1983 with third-generation (1.0 eV) TEC ascending in FY 1985.

Figure 15 contains some of the previously mentioned trends and projections. In addition the solid straight lines in figure 15 represent simple correlations of published total internal losses for thermionic converters producing practical power densities. These line segments reveal that progress was rapid when large improvements were still possible (>2-eV internal losses). But as performance increased the rate of gains diminished (2.0- to 1.7-eV internal losses). This is a common technological relationship. However, these TEC performance improvements occurred while a complete program termination and several major transitions dwarfed usual R&T adversities (refs. 10 and 12).

SOME IMPLICATIONS OF TEC TRENDS

Energy-conversion-technology projections are subjects of important DOE-sponsored studies (refs. 34 and 35). Results of these analyses relating cost of electricity (COE) to overall powerplant efficiency imply long-range influences on the economy and energy conservation as well as on the environment. Figure 16 indicates this relationship (ref. 35). The "'78 TEC, STEAM" points are adaptations of TEC topping data (refs. 20 to 27 and 30) to estimate "30-year levelized cost in mid 1975 dollars" with "fuel cost assumed constant in fixed dollars" ($1/10^6 Btu's). The upper "'78 TEC, STEAM" point covers a range of practically unoptimized ("UNOPT.") results while the lower point represents a partially optimized ("PART. OPT.") TEC topping system (ref. 25). This partial optimization takes advantage of greater efficiencies and far fewer converter modules possible for TEC (with negligible interelectrode losses) operating at 20 to 40 A/cm^2 rather than than near 5 A/cm^2 (refs. 18 and 19; appendix page 13; figs. 4 to 11). Philosophies as well as figures 3 and 4 of reference 25 are very similar to those of reference 18 (appendix).

Figure 16 anticipates near-maximum performances for all advanced conversion systems. For TEC this means "third generation," which the preceding charts depict quite fully: Low internal losses (~1 eV) and high emitter temperatures (to ~1600 K) are necessary for TEC efficiencies (ranging to >35%) required to achieve the "'78 TEC, STEAM" status. This requirement contrasts somewhat with that for megawatt space TEC applications, where high temperatures make moderate efficiencies (~15%) acceptable (refs. 1 to 19). Demonstrated TEC performance is at the threshold in space - half way home

on earth. And TEC gains are continuing (fig. 15).

With expected R&T accomplishments, "'78 TEC, STEAM" projections point to high overall efficiencies (~45% to 47% "UNOPT." and >47% "PART. OPT," including desulfurization losses). Such performance means great energy-conservation and environmental improvements. Furthermore, with the apparent hot-corrosion and slag resistance as well as the thermal-expansion match of silicon-carbide-clad converters (refs. 36 to 40), TEC is one of the few good prospects for direct use in coal-combustion products. And coal utilization means balance-of-payment reversals as well as national energy independence.

The previously mentioned aspects should intensify interest in "TEC bridging of the Carnot-efficiency gap between MHD topping and steam-driven generators." For coal-fired, MHD, TEC, STEAM combinations, calculated overall efficiencies rise above 55 percent - off the chart on figure 16 (refs. 24 and 29).

In topping COE (refs. 20 to 27, except 25) as in space applications (refs. 1 to 19, except refs. 18 and 19), TEC has suffered because of continual apologies for its high-current-density capability: Most designs arbitrarily assign values near 5 A/cm^2. Now references 18, 19, and 25 advocate the efficiency increases and converter-number reductions possible with high-power-density TEC having negligible internal losses. Changing from about 5 A/cm^2 to 20 to 40 A/cm^2 is a prime factor in diminishing TEC-topping COE's from ~46 mills/kW·hr ("UNOPT.") to ~37 mills/kW·hr ("PART. OPT.") on figure 16. And as reference 25 concludes, "we expect that further significant improvements can be made by optimizing the overall system design." Such results should place TEC, STEAM among the best systems on figure 16.

Incidentally, figure 16 (ref. 35) levelizes "costs in mid 1975 dollars" using \$1/10^6 Btu fuel and a 2.00 EPRI levelizing factor. So the present paper converts reference 25 findings to figure 16 ground rules to obtain a compatible comparison. Higher assumed fuel costs, say \$3/10^6 Btu, accentuate the COE difference between STEAM and TEC, STEAM: For \$1/10^6 Btu the TEC, STM COE is ~37 mills/kW·hr compared with STM at ~42 mills/kW·hr, 5 mills/kW·hr or 13.5% greater. And for \$3/10^6 Btu the TEC, STM COE is ~65 mills/kW·hr compared with STM at ~83 mills/kW·hr, 18 mills/kW·hr or 27.7% greater.

In any event optimized TEC topping promises high efficiencies and low COE's as well as good prospects for service in high-temperature coal-combustion products. Such potentialities have very important implications, mentioned previously. Analyses of TEC-specific applications, like on-site coal-fired power cogeneration for electrochemical industries, could increase TEC potentials even more. The major R&T accomplishments needed to achieve these application payoffs are rapid TEC-performance improvements coupled with detailed determinations of low-cost effective materials, fabrication techniques, and maintenance procedures. TEC trends are in the right direction.

APPENDIX

(Excerpted from NASA TM-73844)

SOME TEC BACKGROUND AND THEORY

At present the major space TEC application appears to be nuclear electric propulsion (NEP) (refs. 1 to 3). But analyses that properly recognize the high-temperature, high-power-density advantages of TEC may prove it valuable for solar, radioisotope, and topping utilization in space also. Unfortunately, though, some design-feasibility studies assume without optimization that low or intermediate temperatures and small power densities are required for space TEC (refs. 1 to 3).

The present report offers some theoretic results that emphasize the need to consider greater power densities and higher temperatures within reasonable limits for TEC in space: Converter outputs and efficiencies for 1400-to-2000K emitters with 725-to-1000K collectors make this point.

George Hatsopoulos and Elias Gyftopoulos, long-term international TEC experts, as well as B. Ya. Moyzhes and G. Ye. Pikus, two other world-renowned TEC contributors, elaborate on the thermionic-converter heat engine in their reference works (refs. 4 and 5): For reversible devices the heat supplied isothermally at absolute temperature T_h is $\int dQ_h = \int T_h\, dS_h = T_h \int dS_h$, where $\int dS_h$ is the entropy decrease of the source. Similarly the heat rejected isothermally at absolute temperature T_c is $\int dQ_c = \int T_c\, dS_c = T_c \int dS_c$, where $\int dS_c$ is the entropy increase of the sink. Then according to Carnot the ideal heat-engine efficiency is

$$\lim_{\int dS_c \to \int dS_h} \left[\eta = \frac{\int dQ_h - \int dQ_c}{\int dQ_h} = \frac{T_h - T_c}{T_h} - \frac{T_c}{T_h}\left(\frac{\int dS_c}{\int dS_h} - 1\right) \right] = \frac{T_h - T_c}{T_h} = \eta_c$$

From this basic principle comes the expectation that in general raising the emitter temperature or lowering the collector temperature tends to increase TEC efficiency. Local exceptions to this corollary may occur for optimizations of specific converters. But with freedom of selection for electrode types and materials, enhancement modes, and operating conditions this temperature generalization for TEC efficiency prevails.

Occasionally, disseminated information apparently contends with the idea that TEC efficiencies generally rise with increasing emitter temperatures (ref. 3). At such times reaffirmation of the validity of Nicolas Carnot's thermodynamic legacy seems appropriate. But merely pointing to the preceding equation is perhaps somewhat simplistic. So the present report relies on TEC output and efficiency

calculations based on the assumptions used to produce pages IV-15 to IV-18 of ref. 3: "Back emission should be limited to 10%" for 1400, 1650, and 1800K emitters (2000K included also) with 725, 925, and 1000K collectors. However the present analysis deletes the ref. 3 assumptions that "converter power density should be set at 5 to 6 W_e/cm^2" and that the highest emitter temperature should be used only with the highest collector temperature. Also, assumed interelectrode losses near zero by FY 81 (ref. 6) allow estimates of collector work functions.

The appropriate converter outputs are the current density,

$$J_0 = J_{SE} - J_R, \qquad 1)$$

the electrode voltage,

$$V_0 = \phi_E - \phi_C - V_D - V_A = \phi_E - V_B - V_A, \qquad 2)$$

the voltage at optimum-lead terminals,

$$V_{OL} = V_0 - V_L, \qquad 3)$$

the electrode power density,

$$P_0 = J_0 V_0, \qquad 4)$$

and the effective power density with optimum leads attached to the converter,

$$P_{OL} = J_0 V_{OL} \qquad 5)$$

Here ϕ_E and ϕ_C are emitter and collector work functions, V_D is the interelectrode voltage drop, $V_B = \phi_C + V_D$ is the barrier index or total internal loss, V_A is the equivalent auxiliary input voltage (not used in the present calculations), and V_L is the voltage loss required for optimum leads.

The current-density components correspond to emitter saturation,

$$J_{ES} = A\ (1-R_E)\ T_E^2 \exp\ (-\phi_E/kT_E), \qquad 6)$$

which has a collector-saturation counterpart,

$$J_{CS} = A\ (1-R_C)\ T_C^2 \exp\ (-\phi_C/kT_C), \qquad 7)$$

and to the reverse flow J_R, which includes reflections, backscattering, back emission, and other effects that diminish the output current density. In equations 6) and 7) A and k are Richardson and Boltzmann

constants, T_E and T_C are emitter and collector temperatures, and R_E and R_C are emitter and collector reflection coefficients.

An important theoretic detail relates to a common inconsistency in the treatment of back emission (refs. 7 and 8): In generalized TEC terminology back emission subtracts from the emitter current in obtaining the net output current. This usual definition of back emission requires it to be only that part of the collector emission that reaches the emitter and thereby diminishes the output current according to a net-flow balance at the converter boundaries. Thus back emission is not the saturated collector emission given by equation 7), regardless of R_C modification, because the emission barrier is incorrect: This observation derives from the fact that, in the generally cited TEC power-producing mode, the emitter electron barrier (motive maximum) is a few tenths of a volt (the interelectrode voltage drop) above its collector counterpart. So during steady-state operation the preponderance of collector saturated emission cannot clear the emitter sheath, even in the absence of other deflecting encounters. Therefore most of the collector saturated emission must return to its source nullifying to a large extent its effect on the diminution of the net output current.

Unless the interelectrode loss is much closer to zero than to its currently common value of about a half volt, only a small fraction of the collector emission, the true back emission J_{BE}, will reach the emitter:

$$J_{BE} = A(1-R_{BE})\ T_C^{\ 2} \exp\ (-V_B/kT_C) \qquad 8)$$

In this equation the effective back-emission reflection coefficient R_{BE} comprises R_C and similar coefficients for all interelectrode mechanisms that return collector-emitted electrons to their source--except those for noncollisional repulsion by the emitter sheath. Thus, using equation 8) without R_{BE} produces a conservative estimate of the converter output current. Such an approximation seems reasonable for low cesium concentrations, reduced enhanced-mode pressures, and small interelectrode gaps. Of course, with zero interelectrode losses assumed (ref. 6 for FY 81) as well as negligible interelectrode-reflec tion effects, equations 7) and 8) become identical.

A simplified, yet reasonable estimate of TEC efficiency with optimum-lead losses (η_{OL}) embodies the previously discussed inputs (refs. 4 and 9):

$$\eta_{OL} = \frac{(J_{ES}-J_{BE})\ \{\emptyset_E-\emptyset_C-V_D-V_A-2\left[2.45\times10^{-8}\ \eta_{EC}(T_E^{\ 2}-T_C^{\ 2})/(2-\eta_{EC})\right]^{\frac{1}{2}}\}}{J_{ES}(\emptyset_E+2kT_E)-J_{BE}(\emptyset_E+2kT_C)+5.7\times10^{-12}\left[0.05+7.5\times10^{-5}(T_E-1000)\right](T_E^{\ 4}-T_C^{\ 4})} \qquad 9)$$

Here the last term of the denominator approximates nonelectronic thermal transport while the factor following the first 2 in the numerator

represents the optimum-lead loss V_L. Deleting $2V_L$ from equation 9) transforms that expression into one for the TEC electrode efficiency η_{EC} used here to compute the optimum-lead loss. Of course, the electrode efficiency is the true converter evaluation analogous to other power-generator performance ratings. But because of relatively high TEC current densities and low voltages the optimum-lead efficiency seems more pragmatic.

Theoretic TEC outputs and efficiencies for converters with 10-percent back emission and optimum leads appear parametrically in figures 1, 2, and 3 for 725, 925, and 1000K collectors. Each figure comprises plots of efficiency, voltage, and power density as functions of current density for 1400, 1650, 1800, and 2000K emitters.

Without exception, for a given collector temperature, all performance curves for higher emitter temperatures rise above those for the lower emitter temperatures. This observation would have gratified Nicolas Carnot.

The efficiency curves reach values very close to their maxima above 5 A/cm^2 for the 1400K emitters; 20 A/cm^2 for 1650K emitters; 30 A/cm^2, 1800K; and 40 A/cm^2, 2000K.

The two preceding paragraphs imply that studies of any TEC system should evaluate parametrically the effects of converters with emitters hotter than 1650K and current densities greater than 5 A/cm^2 (refs. 1 to 3). Table 1 for 925K collectors (refs. 2 and 3) further emphasizes this observation. The underlined Table 1 entries indicate output and efficiency improvements (for converters with optimum leads) resulting from raising the emitter temperature from 1650K to 1800K at 5 A/cm^2 and at 30 A/cm^2.

These underlined values also reveal the significant output and efficiency gains for TEC operation at 1800K and 30 A/cm^2 as compared with 1650K and 5 A/cm^2 (refs. 1 to 3): <u>The 28.5% increase in optimum-lead efficiency</u> means lighter radiators and either more output power or smaller nuclear reactors and lighter shield-dependent weights for NEP. <u>The 10.8% higher optimum-lead voltage</u> requires less power conditioning capability and results in lower transmission-line losses for a given quantity of output power. <u>The 560% gain in effective output power density</u> allows many fewer converters and associated current-collecting bus bars for a given output-power level. <u>And of course the higher emitter temperature</u> (coupled with greater efficiency) enables the use of substantially fewer and/or smaller emitter heat pipes. This reduction in turn should produce significant decreases in shielding-related as well as reactor weights. The higher emitter temperature can also make possible considerably increased collector temperatures if parametric studies indicate the need for lower radiator weights (the T^4 influence).

The previously enumerated advantages of 1800K, 30 A/cm^2 TEC operation over the 1650K, 5 A/cm^2 case have obviously strong effects on NEP specific-weight reductions. So the importance of true overall system optimization with parametric TEC inputs should not be underestimated.

Omitted tabulations similar to those of Table 1 are also available for collector temperatures of 725K and 1000K. And as figures 1 to 3 attest, the order of performance remains unchanged: For a given collector temperature the highest emitter temperature produces the best TEC performance; the lowest emitter temperature gives the poorest TEC performance.

If the only emitter, collector combinations considered were 1400K with 725K, 1650K with 925K, and 1800K with 1000K all at 5.5 W/cm^2 as in reference 3, the TEC-output relationships would appear quite different from those in figures 1 to 3. But a parametric TEC-optimization study should evaluate each collector temperature with each emitter temperature. When existing converter-component capabilities preclude such pairings, appropriately directed technology advancements may render them possible in the near future.

Reference 3 states that "the higher temperature converters are limited to higher work function materials, and thus eventually extrapolate to lower operating efficiencies.'. But the 1800K emitter work functions in the table are obtainable with cesiated tungsten, for example, without invoking oxygenation. Such work functions are even more readily accessible with rhenium and still more easily attainable with iridium.

As for the collector work functions in the preceding table, they are well within reach of cesiated, oxygenated tungsten: This collector has a work-function minimum of 1.21 eV according to recent measurements (ref. 9). Unoxygenated minimum cesiated work functions run 1.45 eV for rhenium (ref. 4) and probably 1.4 or lower for 111 iridium (refs. 7, 8, and 10 to 14). And tungsten, rhenium, and iridium are all satisfactory for 1800K-emitter service.

Incidentally the calculations for figures 1 to 3 give results rather centrally located among those from other TEC efficiency models for 10% back emission and zero arc drop (Private communication with G. D. Fitzpatrick of Rasor Associates, Inc.). The variation occurs because of differences in loss approximations. A comparison of TEC efficiencies appears in Table 2.

Table 2 lists extremes of conditions primarily to compare TEC-efficiency models over wide ranges. But these values also strongly imply the desirability of high-temperature, high-power-density thermionic energy conversion for space.

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TABLE I: EFFECTS OF EMITTER TEMPERATURE AND CURRENT DENSITY ON THERMIONIC CONVERSION PERFORMANCE

Emitter Temp., K	1400	1650	1800	2000	14[illegible]	1650	1600	2000	1[illegible]	1650	1800	2000	1400	1650	1800	2000
Collector Temp., K	925	925	925	925	925	925	925	925	925	925	925	925	925	925	925	925
Current Density, A/cm²	5	5	5	5	10	10	10	10	20	20	20	20	30	30	30	30
Output Voltage, V																
V_0	0.59	1.02	1.28	1.63	0.57	0.98	1.23	1.56	0.54	0.93	1.17	1.50	0.52	0.91	1.14	1.46
V_{0L}	0.53	0.93	1.18	1.52	0.50	0.88	1.12	1.44	0.47	0.84	1.07	1.37	0.45	0.81	1.03	1.33
Power Density, W/cm²																
P_0	3.0	5.1	6.4	8.1	5.7	9.8	12.3	15.6	10.7	18.7	23.5	29.9	15.6	27.2	34.3	43.8
P_{0L}	2.6	4.7	5.9	7.6	5.0	8.8	11.2	14.4	9.4	16.8	21.3	27.4	13.6	24.4	31.0	40.0
Efficiency, %																
η_0	22.4	28.4	29.4	28.6	23.3	31.3	33.8	34.9	23.7	32.9	36.5	39.2	23.5	33.5	37.4	40.9
η_{0L}	17.4	23.5	24.9	24.9	17.7	25.4	28.0	29.6	17.7	26.3	29.7	32.7	17.5	26.4	30.2	33.8
Emitter Work Function, eV	2.12	2.55	2.80	3.15	2.04	2.45	2.70	3.03	1.95	2.35	2.59	2.91	1.90	2.29	2.53	2.84
Collector Work Function, eV	1.53	1.53	1.53	1.53	1.47	1.47	1.47	1.47	1.42	1.42	1.42	1.42	1.38	1.38	1.38	1.38

TABLE 2: TEC EFFICIENCIES

Emitter Temp, K	60 A/cm² Collector Temp = 725K Collector Work Function ≅ 1.0 eV		10 A/cm² Collector Temp. = 1000K Collector Work Function ≅ 1.6 eV
2000	~ 40%	R. Breitwieser	~ 19%
1400	~ 32%	"	~ 12%
2000	~ 41%	Rasor Associates, Inc.	~ 24%
1400	~ 29.5%	"	~ 14%
2000	~ 50%	Thermo Electron Corp.	~ 28%
1400	~ 35.5%	"	~ 13%
2000	~ 43.4%	J. Morris	~ 27%
1400	~ 30.3%	"	~ 13%

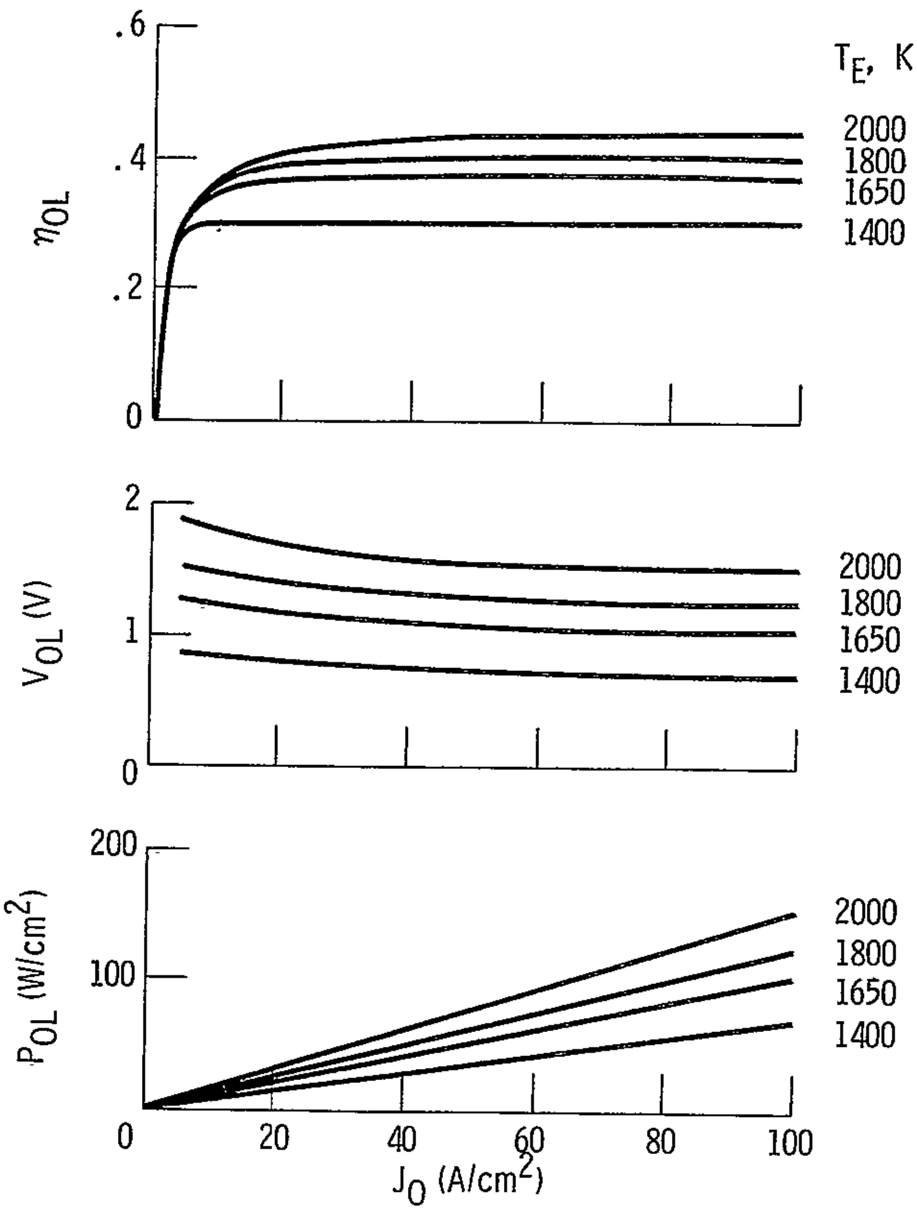

Figure 1. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 725 K with 10 percent back emission.

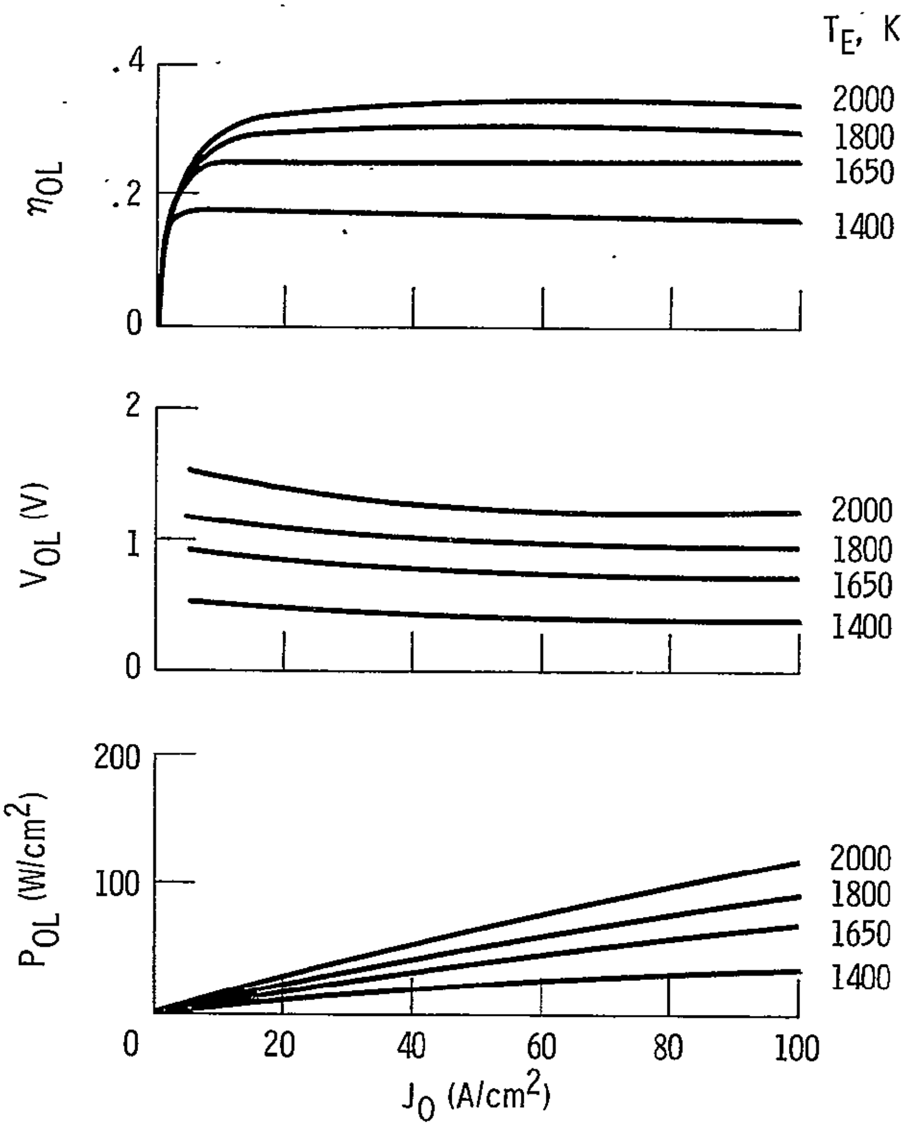

Figure 2. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 925 K with 10 percent back emission.

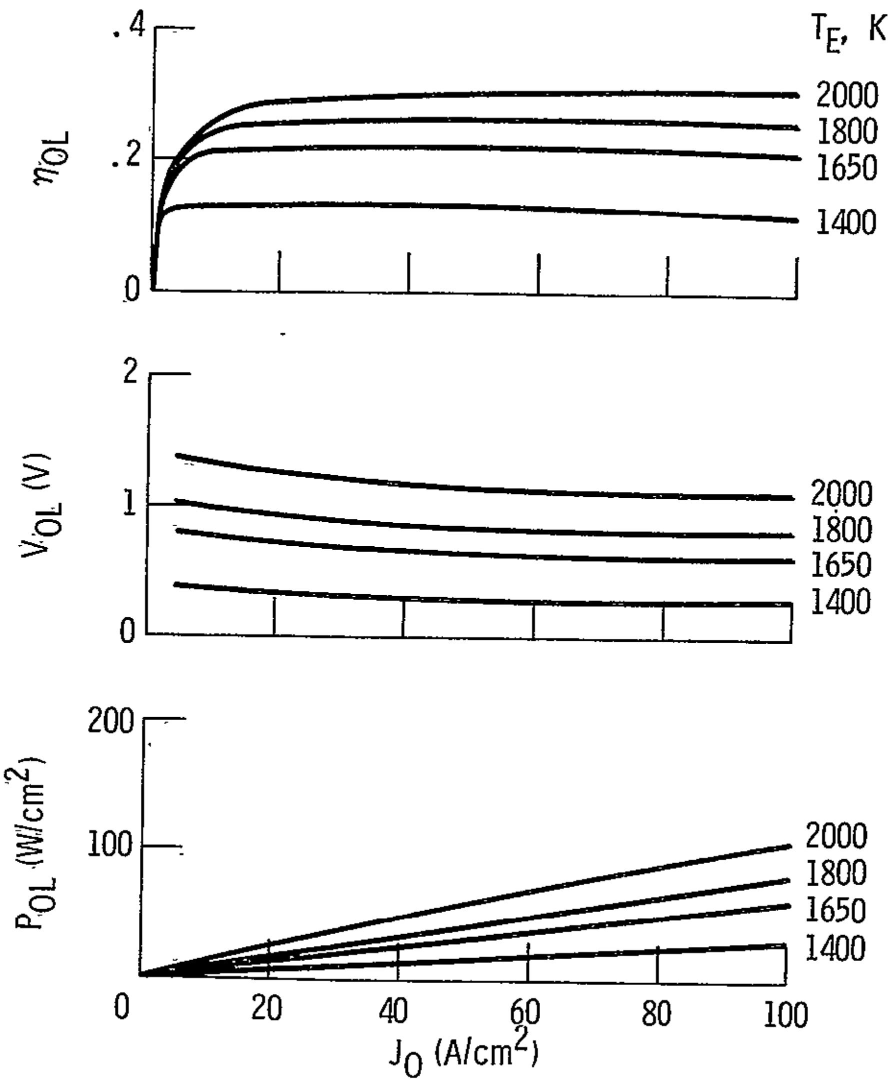

Figure 3. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 1000 K with 10 percent back emission.

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TABLE 3 THERMIONIC PERFORMANCE MILESTONES AND POTENTIAL APPLICATIONS

End of Fiscal Year	Barrier Index[1] V_B (eV)	Efficiency, %[2] 1400 K	1700 K	Potential Application
1973	2 1	4 3	12 4	In core space reactor (8 mil spacing)[3]
1975	2.0	7 2	14.1	Oxygen additive converter (40 mil spacing)
1976	1.9	9.0	16.5	Laboratory converter (tungsten oxide collector)
1977	1.8	11.5	18 6	Radiosotope thermoinoic generator Solar thermal electrical power plant
1978	1.7	14.0	21.3	Out of core space reactor (40 mil spacing) Hydrocarbon auxiliary power unit
1979	1.6	16.8	23.7	Thermionic topped fossil fuel power plant
1980	1.5	20 0	26.4	Improved performance for all applications

1 Established at 6 amps/cm^2 in a laboratory converter and at optimum spacing.

2. Calculated at optimum current density

3 Reduced to engineering practice in U S and U S S R.

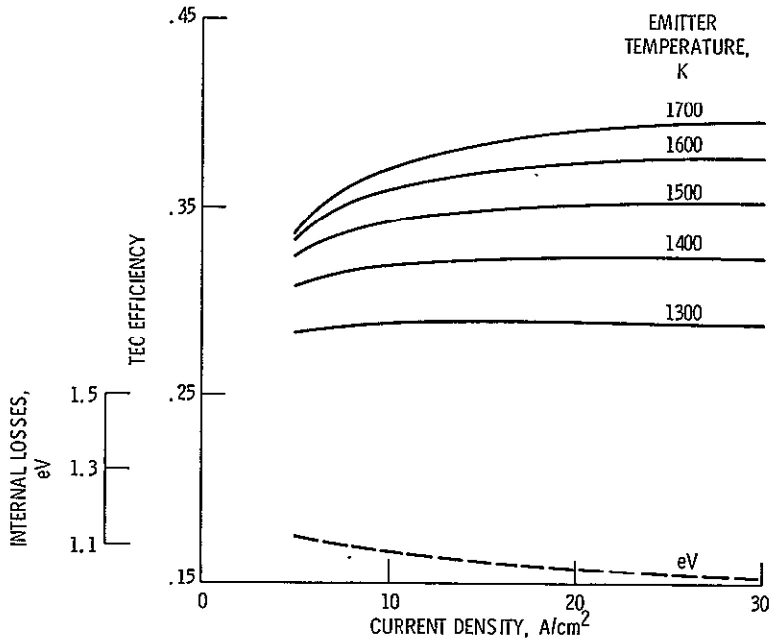

Figure 4. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 700 K collectors with 1300-to-1700 K emitters.

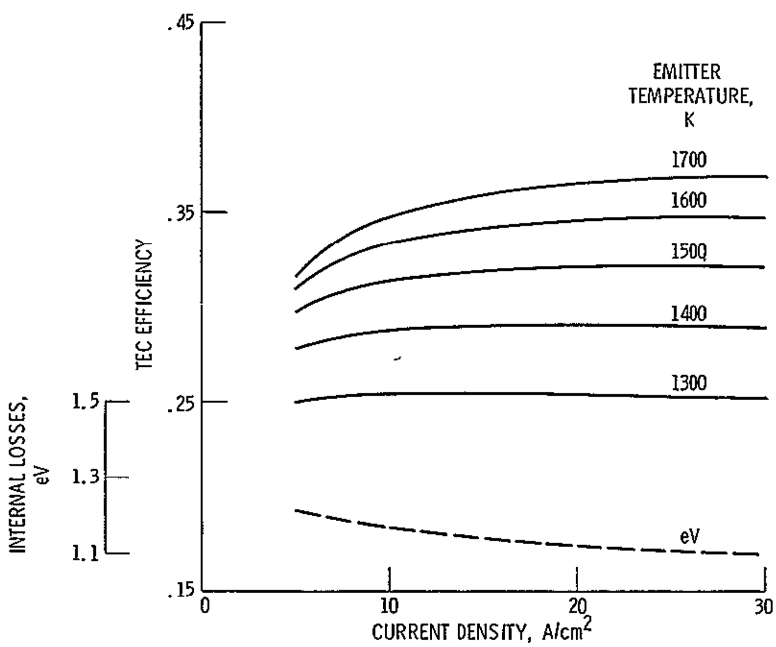

Figure 5. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 750 K collectors with 1300-to-1700 K emitters.

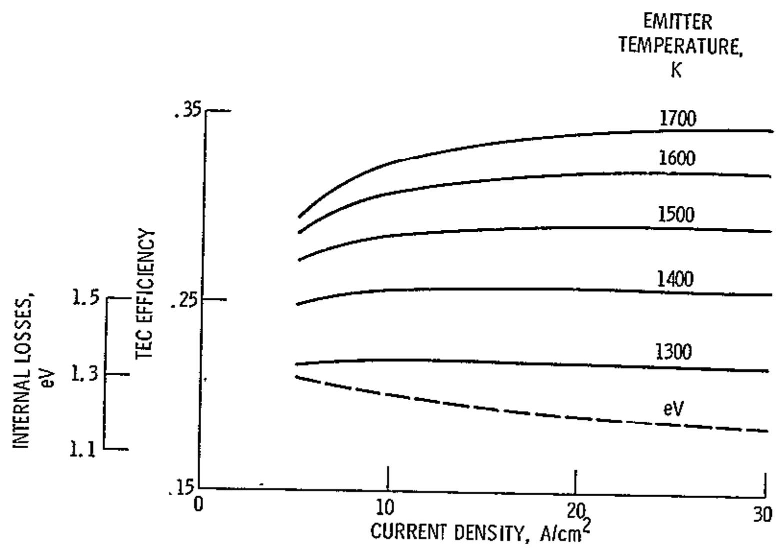

Figure 6. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 800 K collectors with 1300-to-1700 K emitters

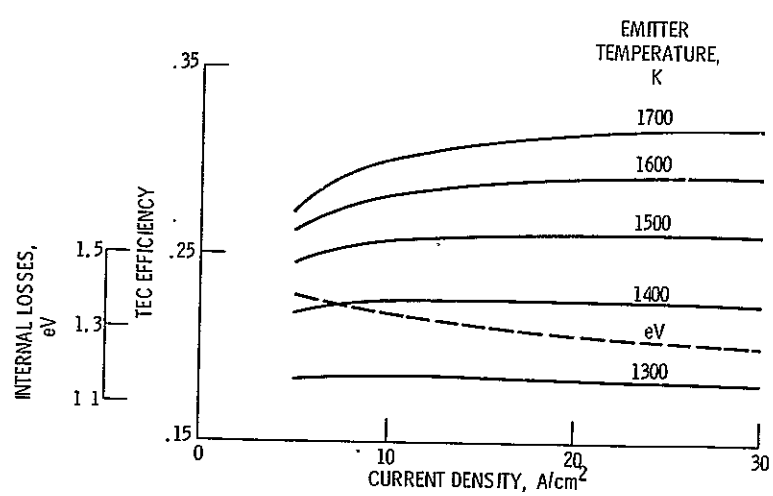

Figure 7. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 850 K collectors with 1300-to-1700 K emitters

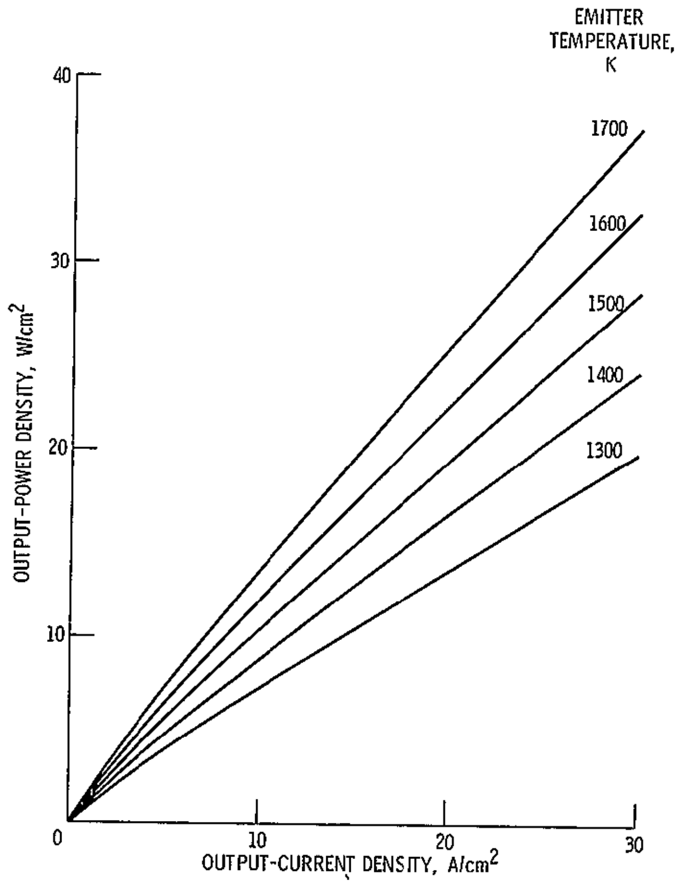

Figure 8. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output current density for 700 K collectors with 1300-to-1700 K emitters.

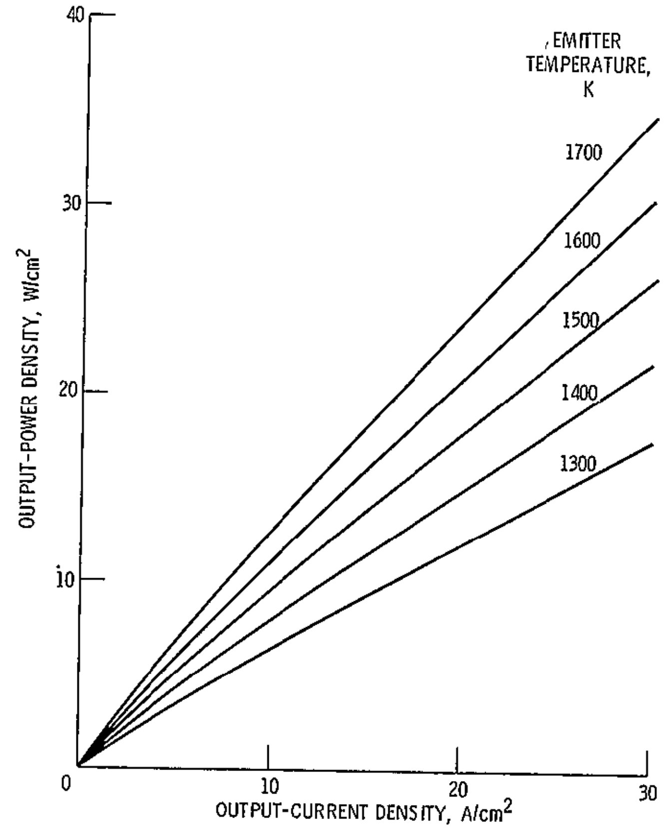

Figure 9. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of ouput output-current density for 750 K collectors with 1300-to-1700 K emitters.

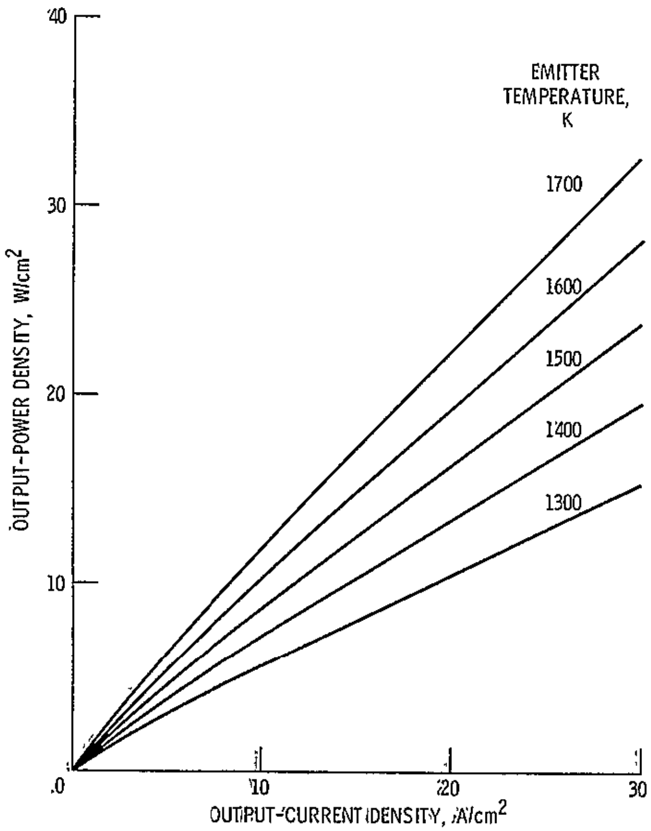

Figure 10. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output-current density for 800 K collectors with 1300-to-1700 K emitters.

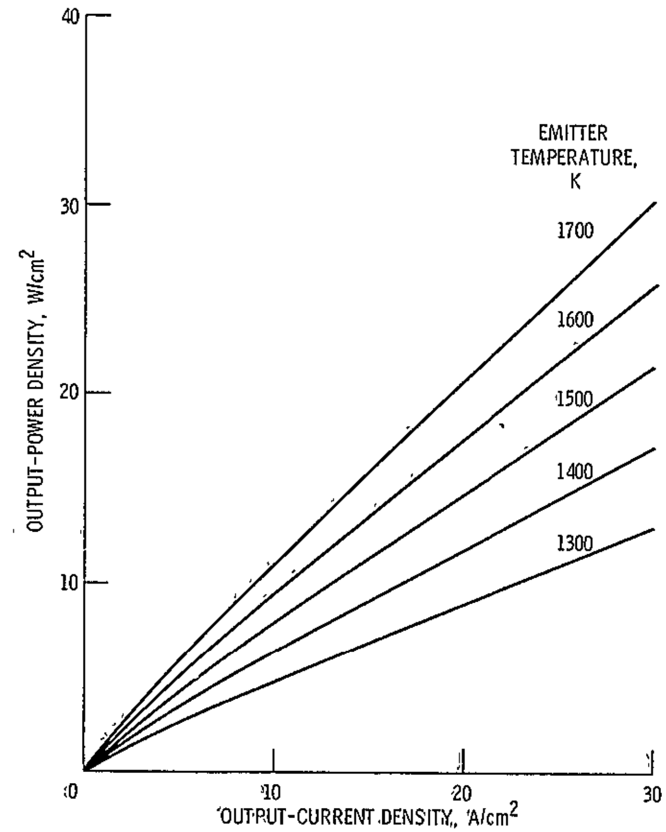

Figure 11. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output current density for 850 K collectors with 1300-to-1700 K emitters.

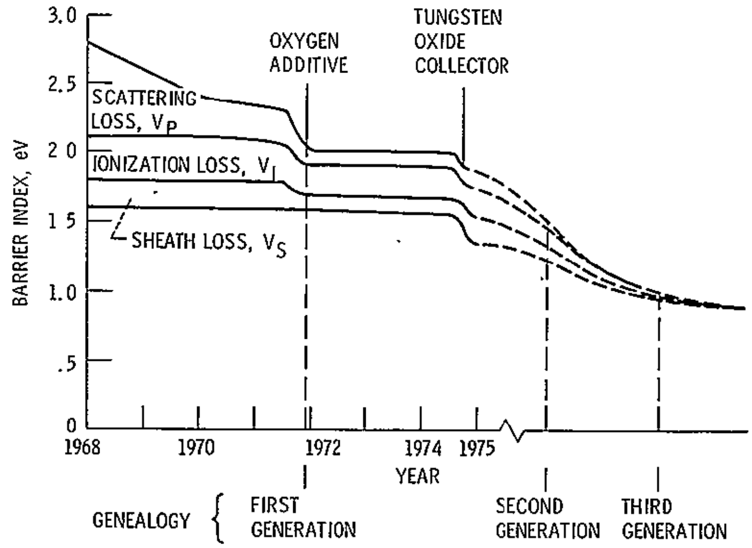

Figure 12. - Reduction of losses in thermionic converter.

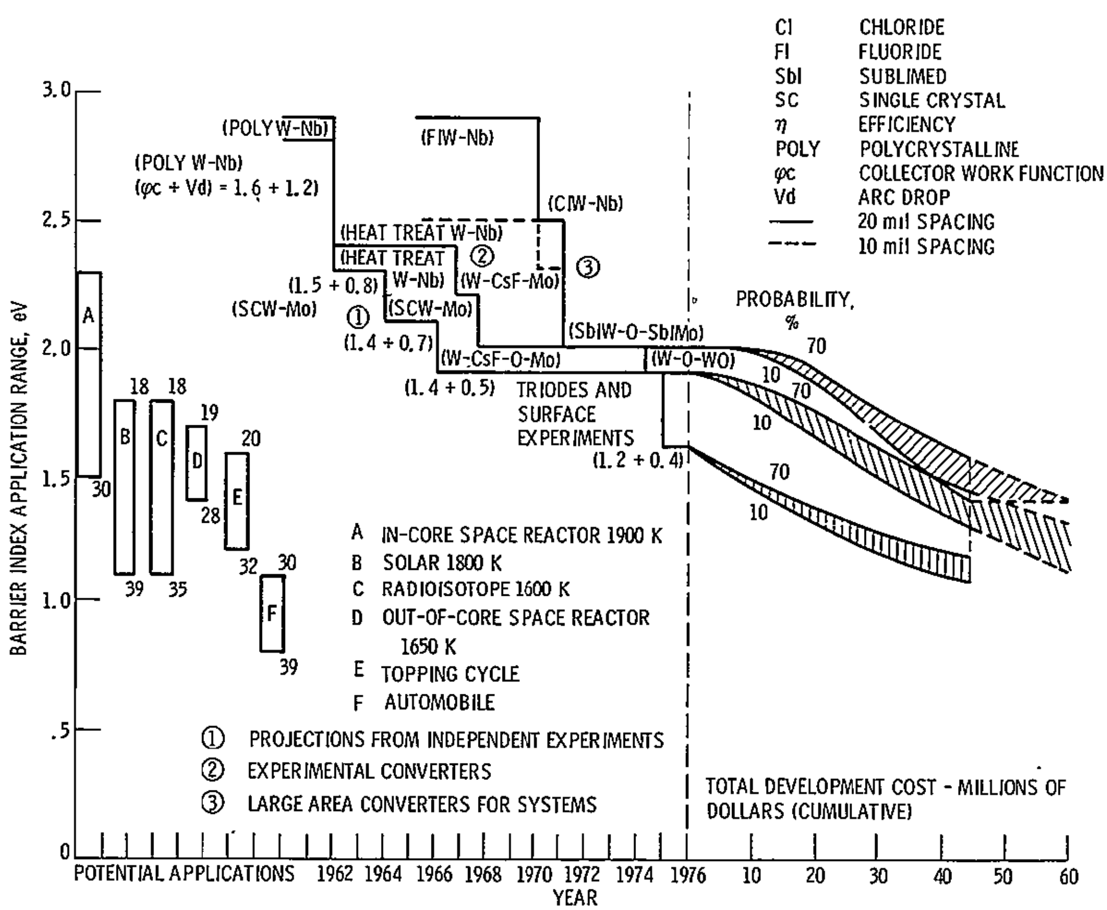

Figure 13. - Thermionic progress, projections and potential applications.

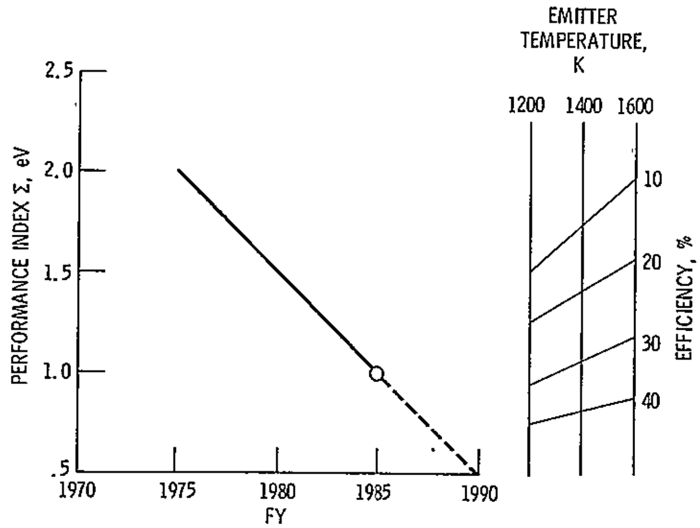

Figure 14. - Performance index objectives of current thermionic program. (Efficiency for any performance index and emitter temperature can be determined using appropriate temperature scale on right.)

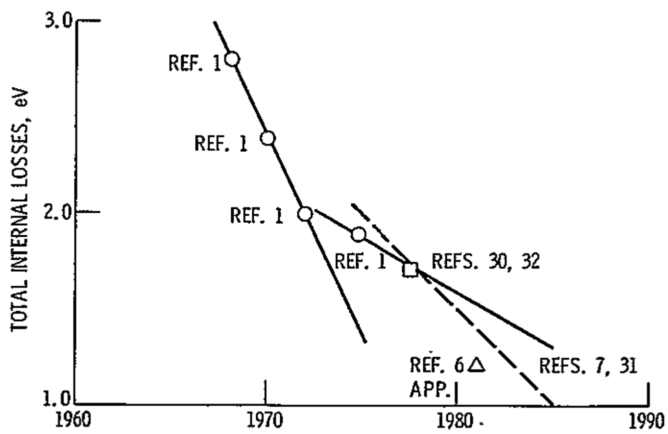

Figure 15. - TEC trends.

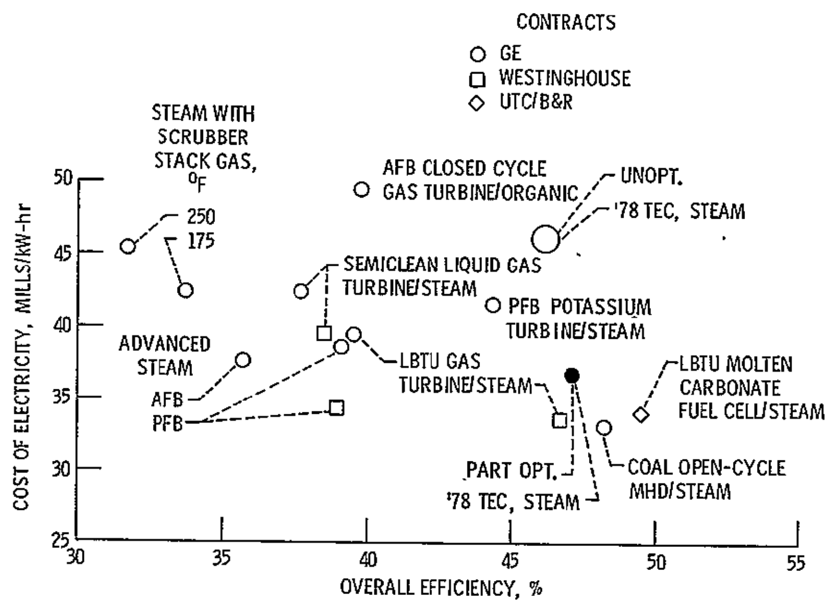

Figure 16. - ECAS Phase 2 results using 30 year levelized cost in MID 1975 dollars. Fuel cost assumed constant in fixed dollars.

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16. Abstract

Years of R&T work and continued consultation in thermionic energy conversion (TEC) allow some observations on TEC trends. Extrapolations of the growth curve guided by recent technological advances are the bases for projections of space and terrestrial TEC applications. Such predictions are available in previous TEC publications. And this presentation comments on that aspect of TEC R&T.

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